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FROM: PROI (STINFO) 12 Apr 2001

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-AB-2001-082**
Mark Archambault, Richard Cohn, Doug Talley, Oshin Peroomian, "Computational Analysis of a Single-Element, Shear-Coaxial, GH_2/GO_2 Engine"

40th AIAA Aerospace Sciences Meeting & Exhibit **(Statement A)**
(Reno, NV, 14-17 Jan 2001) (Deadline: 04 May 01)

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Computational Analysis of a Single-Element, Shear-Coaxial, GH_2/GO_2 Engine

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A computational and experimental program of research in gas/gas injection has been initiated in support of staged combustion cycle engines. The overall objective of this research is to develop a design methodology for gas/gas injectors. This paper, however, focuses on a computational methodology to efficiently, accurately, and robustly obtain high-fidelity solutions of combusting rocket engine flows to gain a knowledge and understanding of their features. To that end, simulations of a single-element, shear-coaxial, H_2/O_2 engine are being performed to characterize its flowfield and to validate the CFD++ flow solver for this class of problems. Thus far, solutions have been obtained on a grid containing 53740 cells, three to four times the number of cells used by other researchers,[1,2] using four and eight processors on an SGI Origins 2000 computer. The code solves the two-dimensional, compressible, real gas equations with a second-order accurate spatial discretization scheme. Currently, a standard, realizable k-epsilon turbulence model is employed to resolve the turbulent mixing, and the constant-pressure combustion model is used in combination with a 9 species, 19 reactions finite-rate kinetics model.

A number of computational issues arose during these calculations that will be discussed. The first involved how to ignite the flow. Initially, a cold flow solution was obtained to be used as the starting condition for the combusting calculation. The first attempt to ignite the flow was made by heating the lip of the injector between the oxygen post and hydrogen annulus to various temperatures in the range of 2500-3500K. When this failed, a floating heat source (arbitrary box within the domain) was positioned approximately five inches downstream of the injectors and the temperature within the box artificially raised to 2500K. This location corresponds with the location of the igniter in the actual hardware. While the gases did begin to react, the location of the heat source caused significant slowing in the convergence rate of the calculation because the flame had to burn back to the injector face and then the transient had to flush its way out of the chamber. It was finally decided to eliminate the cold flow solution and place the heat source immediately downstream of the injectors where the gases would begin to burn as soon as they entered the chamber.

A second issue that arose had to do with the attachment and stability of the flame. Getting the flame to properly attach to the lip of the injectors proved to be difficult. Early versions of the numeric algorithm caused the flame to lift a few inches from the lip. To resolve this area better (in an attempt to get the flame to attach) the grid was refined, but that, combined with the second-order accuracy of the numerical scheme, caused the flame to become chaotic, break up, and ultimately blow out. It was concluded that part of the problem was caused by the converging section of the nozzle at the end of the domain. Many preconditioning combustion algorithms cannot handle low-speed to high-speed flows in the same calculation, such as in a rocket engine simulation where the flow is accelerated from near-stagnant conditions upstream to sonic and supersonic speeds through the throat and nozzle. This can introduce artificial transients into the solution, causing difficulties in addition to those already present due to the unsteady nature of the flow. To resolve these issues, the nozzle section was removed and the chamber pressure was imposed at the downstream boundary. Moreover, the algorithm was modified to allow the pressure, temperature, and species to equilibrate properly at each iteration.

Figures 1 and 2, containing contours of temperature and OH concentration, respectively, depict a relatively smooth solution that is attached at the lip of the injectors. Though it is not clearly visible in these images, there remains some unsteadiness in the flow caused by the shear layer, as evidenced by waviness in the flame sheet. In addition, Figures 3–5 show profiles of hydrogen mole fraction, oxygen mole fraction, and mean axial velocity, respectively, that compare well with experimental data[2,3] and previously reported simulation results.[1,3] Minor discrepancies between the calculation and the experimental data have been explained as effects in the experiment that were not modeled, such as a nitrogen curtain purge to protect the optical access and a shear layer that may have been fluctuating in and out of the probe volume, smearing the data averaging. Further, we see that the hydrogen diffuses radially with increasing distance from the injectors, causing the shear layer to thicken. The oxygen, however, does not diffuse as much, being hemmed in by the hydrogen and the flame. This is consistent with earlier observations by other investigators.[2,3] Additional time-accurate and time-averaged solutions will be presented and discussed, including contours and profiles of other species and turbulence characteristics.

Others have noted[1] that specification of the inlet boundary conditions is essential to accurately predict the shear layer inside the chamber. For this reason, the injection system, including the plenum chamber and the inlet stream direction changes, will be modeled and the results examined to see if, by sufficiently modeling these features upstream of the injector face, the sensitivity to the upstream boundary condition can be reduced. Whether or not the sensitivity can be reduced, it is important to model the injection system (in the absence of experimental data that could be used as an upstream boundary condition), because pressure waves can travel back into the injector tubes, significantly altering the chamber inlet conditions. Because of their availability within the code, several turbulence models will be evaluated in an effort to determine how sensitive the solutions to this class of problems is to those models.

While the objective of this paper is to discuss a computational methodology to obtaining detailed solutions to this class of rocket engine flows and comparing results to previously published data, future work will focus on further validation of the code using data obtained experimentally in-house. Multidimensional effects will be examined and various parametric and sensitivity studies will be performed.

Several conclusions will be drawn, including how the nature of the physical problem requires a creative approach so as to capture the features of the flow. Further, new insights into using a finer grid and a time-accurate solution will be discussed. Because results of modeling the injection system have not been previously reported, conclusions based on the sensitivity to the far-upstream boundary conditions such as the inlet velocity profile and turbulence intensity will be presented. Finally, the paper will address the question of when can one, in an unsteady flow, use mathematical and numerical tricks and to what extent can they be used to obtain a meaningful solution, and when must one resort to fully time-dependent solutions to capture the essence of the flow.

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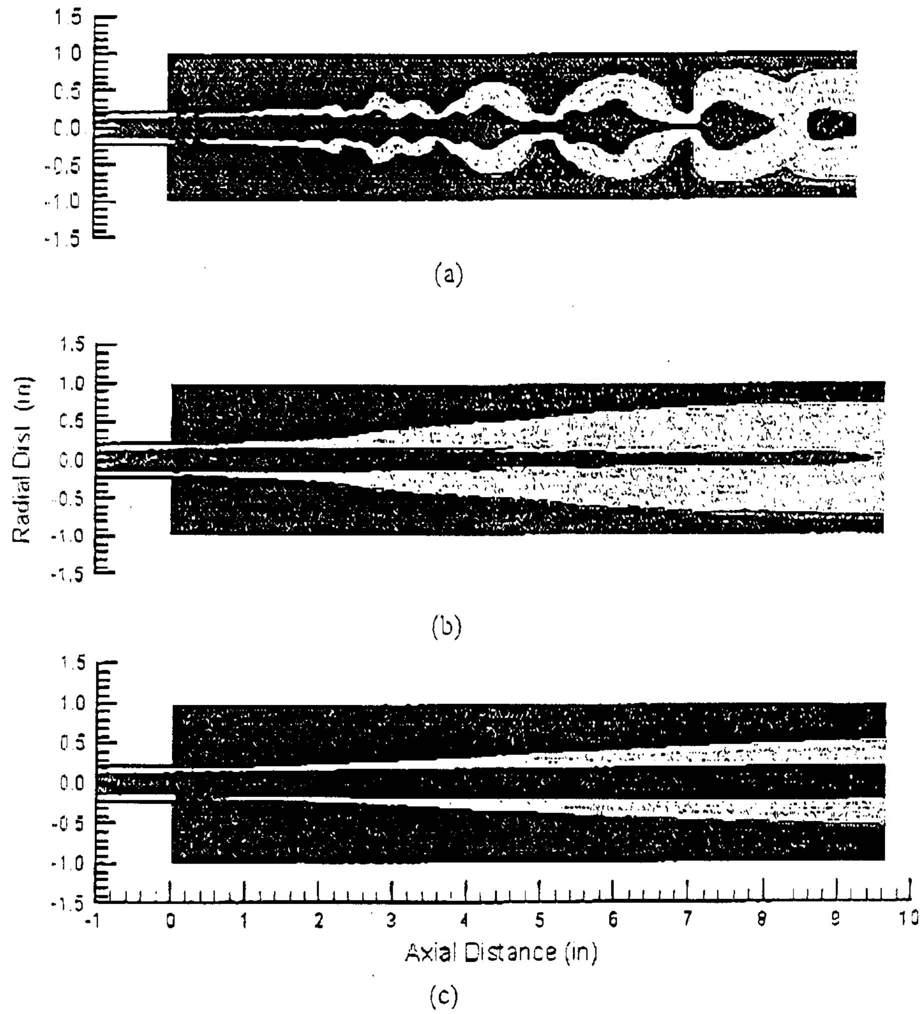
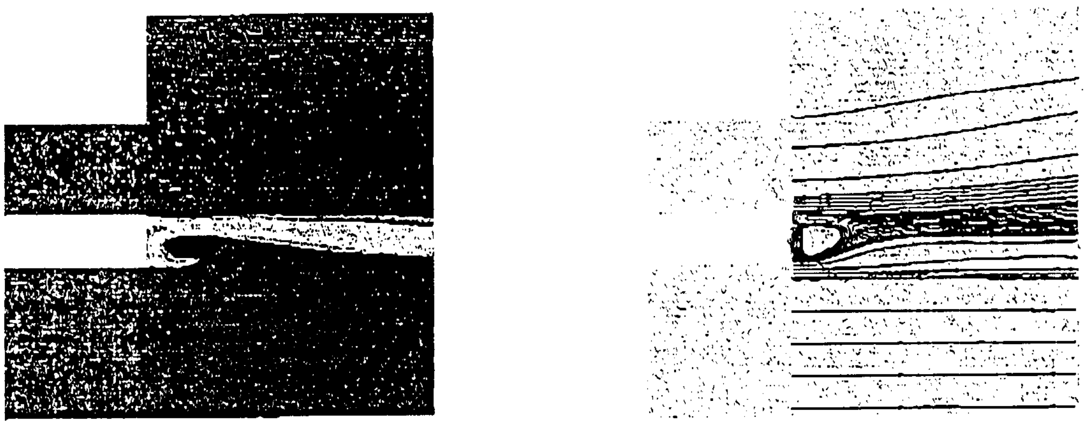


Figure 1. OH concentration contours from (a) instantaneous, (b) averaged time-accurate, and (c) "quasi-steady" solutions.



(a) (b)

Figure 2. (a) OH concentration contours and (b) stream traces in the vicinity of the flame attachment point at the lip of the injectors.

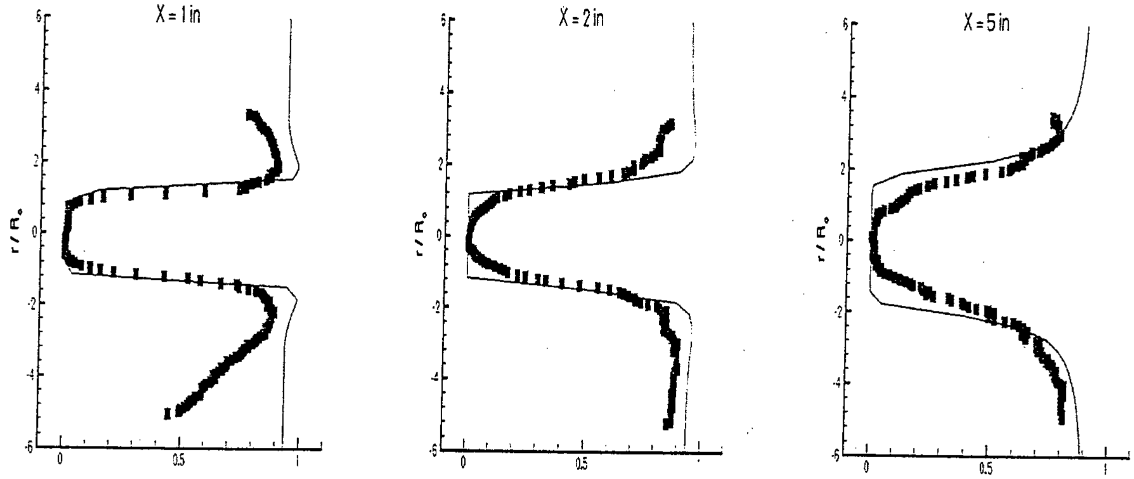


Figure 3 Hydrogen mole fraction profiles at 1 in, 2 in, and 5 in, respectively, downstream of injector face

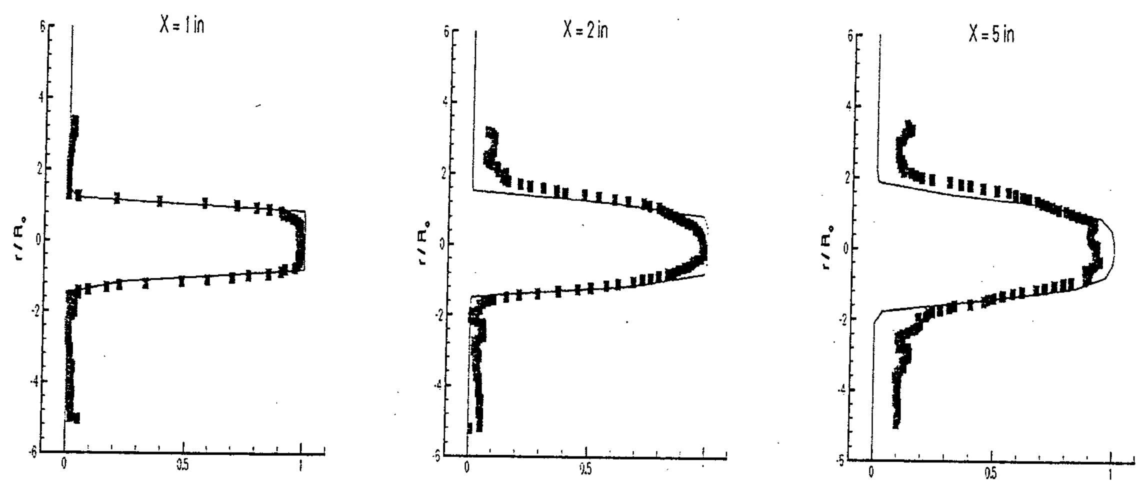


Figure 4 Oxygen mole fraction profiles at 1 in, 2 in, and 5 in, respectively, downstream of injector face

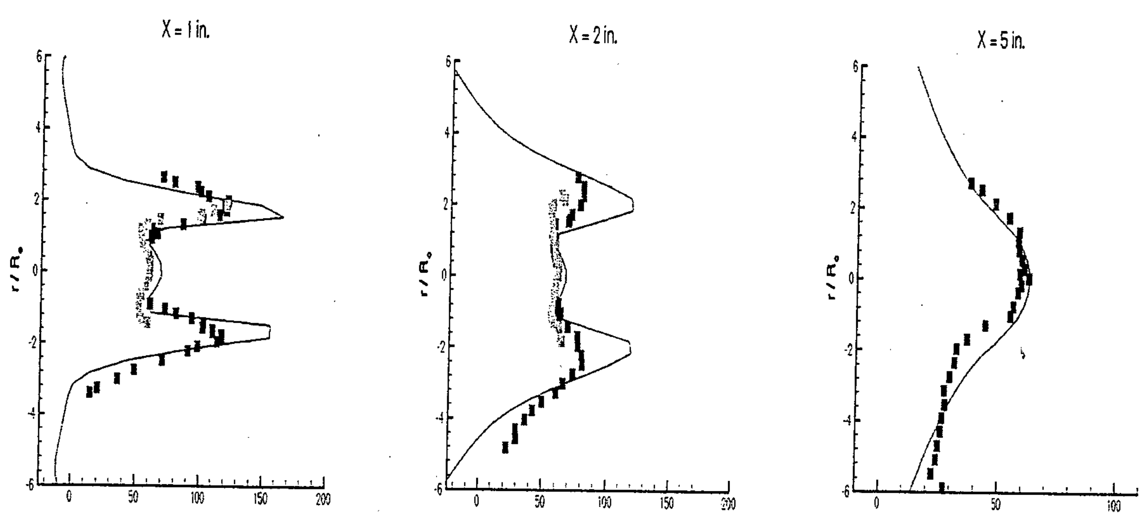


Figure 5 Mean axial velocity (m/s) at 1 in, 2 in, and 5 in, respectively, downstream of injector face